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Energy use and CO_2 emissions in Mexico's iron and steel industry

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Abstract

Energy use and carbon dioxide emissions for the Mexican iron and steel industry are analyzed from 1970 to 1996. To assess the trends in energy use and carbon dioxide emissions, we used a decomposition analysis based on physical indicators to decompose the intra-sectoral structural changes and efficiency improvements. We used a structure/efficiency analysis for international comparisons, considering industrial structure and the best available technology. This study shows that steel production growth drove up primary energy use by 211% between 1970 and 1996, while structural changes (production and process mix) decreased primary energy use by 12% and energy efficiency changes drove down energy use by 51%. In addition, carbon dioxide emissions would have increased by 9% if the primary fuel mix had remained constant at 1970 levels. © 2001 Published by Elsevier Science Ltd.

1. Introduction

Energy use in the Mexican industrial sector has experienced important changes in the last two decades relating to transformations of its domestic economy. In previous studies [1,2], we have shown that a real change in energy intensity was the most important factor in the overall decline of energy use and CO_2 emissions in the Mexican industrial sector. Real changes in energy intensity were explained by different factors, depending on the industrial sub-sector. In this paper, we analyze the factors that influenced energy use in the Mexican iron and steel industry, the largest energy consuming and energy-intensive industry in the country.

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In 1996, the iron and steel industry represented 3.4% of Mexican industrial value added and 17.5% of industrial final energy consumption [3,4]. In terms of production, this industry manufactured 13.2 million metric tonnes (mt) of crude steel, placing it in 15th place in the overall world production [5]. From 1970 to 1996, total primary energy consumption and total carbon emissions of the iron and steel industry increased at an annual growth rate of 3.8%. However, the primary specific energy consumption (energy/mt of crude steel) dropped by 27.0%, and CO_2 emissions intensity (mt C/mt of crude steel) declined by 21.9%. To understand the contributions of activity, structural shifts, fuel switching and real intensity changes in energy use and CO_2 emissions, we utilized an energy consumption decomposition analysis approach based on an average parametric Divisia (AVE-PDM) indices [6,7] and a Physical Production Index [8].

The analysis is carried out in stages. First, we describe the iron and steel production process. Second, we present trends in activity, primary energy and carbon dioxide emissions of the Mexican iron and steel industry. Third, we introduce the methodology used to analyze trends in energy consumption and carbon dioxide emissions. Finally, we present our results, an international comparison of the Mexican iron and steel industry with five of the largest iron and steel world producers and our conclusions.

2. Iron and steel production process

The first step in steel manufacturing is the reduction of iron ore to pig iron in blast furnaces or direct reduced iron (DRI, also called sponge iron) in direct reduction reactors. The generation of the reduction gases, mainly carbon monoxide and hydrogen, that removes the oxygen from the iron ore is produced in the blast furnaces (BF) by partial combustion of the coke; while in the direct reduction process natural gas is reformed to reduce the iron ore. It is important to note that sponge iron has different properties than pig iron and it is used as a high quality alternative to scrap in secondary steel making.

In primary steel making, pig iron is introduced as hot metal in open hearth furnaces (OHF) or in basic oxygen furnaces (BOF) to produce crude steel. The optimum hot metal ratios for BOF and OHF are from 70 to 90% and from 30 to 60%, respectively. Other inputs in this process are steel scrap, limestone and oxygen [9]. The net energy consumption in the BOF is minimal because the oxidation of carbon in the hot meal can take place with the energy content of the molten iron. In addition, an oxygen lance is externally produced with electricity to augment combustion. On the contrary, the OHF requires a large amount of energy input to melt the high share of steel scrap with the hot metal, and it has a lower productivity [10].

In secondary steel making, DRI and scrap are added to the electric arc furnace (EAF) in different amounts: 80% of sponge iron and 20% of scrap for the DRI–EAF process, or 100% of scrap in the scrap–EAF process [9].

Once the crude steel is obtained through the primary or secondary steel making routes, the next step consists of the manufacturing of semi-finished products. Historically, liquid steel was cast into ingots and the ingots were subsequently reheated and rolled to produce billets and slabs. Currently, the liquid steel is continuously cast into slabs and billets, saving energy and reducing material losses. Then the steel products are shaped in different products by the final rolling stages. Profiles, sheets and wire are produced in hot rolling mills; where the steel is first reheated and then introduced in heavy roller sections to reduce its thickness. Finally, thinner sheets are obtained through pickling, cold rolling, annealing and tempering [10].

3. The Mexican iron and steel industry

3.1. Activity trends

From 1970 to 1996, Mexican steel production grew at an average annual rate of 4.8%. However, the production growth was not constant in the overall period. From 1970 to 1980 production grew at an annual rate of 6.3% due to the expansion of Mexican oil exports. Additionally, during the 1970s, the Mexican economy was based on policies that supported the expansion of the industry through energy and transportation subsidies, financial incentives and duties protection. During this time, several strategic iron and steel companies were state owned.

After 1981, the oil boom ceased, and a national economic recession triggered a decline in steel demand until 1989. During this period, steel production increased by only 1.0% annually, steel exports grew steadily and iron imports dropped abruptly. Between 1989 and 1991 all the state owned companies of this industry were privatized. From 1991 to 1996, private investment in expansion and modernization of iron and steel integrated plants grew, and the installed capacity of the secondary steel making plants and mini mills increased. National steel production increased at an annual growth rate of 10.6% in this period. Table 1 summarizes the average annual growth rates.

Table 1
Annual growth rates for iron and steel production by process and for energy consumption by source in the Mexican iron and steel industry

	Overall period				
	1970–1996	1970–1980	1980–1989	1989–1991	1991–1996
Production					
Iron making	5.0%	8.9%	0.4%	−0.7%	8.1%
BF	3.7%	8.3%	−1.3%	−4.2%	7.4%
DRI	7.2%	10.3%	3.2%	5.5%	9.5%
Steelmaking	4.8%	6.3%	1.0%	0.7%	10.6%
OHF	−9.8%[a]	−5.1%	−5.4%	−43.5%	–
BOF	12.5%[b]	–	1.1%	2.7%	8.6%
EAF	6.6%	6.9%	3.0%	6.1%	13.0%
Energy consumption					
Total primary energy	3.8%	5.8%	3.3%	−6.4%	5.2%
Coke	2.4%	4.1%	−0.1%	−10.4%	9.4%
Natural gas	4.2%	6.3%	1.3%	2.1%	6.4%
Fuel oil	6.1%	6.3%	12.4%	−3.7%	−1.2%
Electricity	5.1%	7.5%	7.3%	−9.5%	2.4%

[a] The last OHF production unit closed in 1992, the average annual growth rate considers the period from 1970 to 1991.
[b] The BOF production began in 1972, the growth rate considers from 1972 to 1996.

In terms of iron and steel production processes, the share of production of the different processes varied between 1970 and 1996. In this period, pig iron production increased at an annual growth rate of 3.7%, while DRI production increased 7.2% per year (see Table 1). Likewise, the shares of the production of primary steel by the BF–OHF and BF–BOF routes and of the secondary steel by the DRI–EAF and scrap–EAF routes have also changed. In the early 1990s, steel production at OHFs disappeared completely and was replaced by more efficient BF–BOF production in the integrated plants. In addition, electric steel production increased due to the growth of DRI production and to the expansion of the installed capacity of the scrap based EAF secondary steel plants. In the manufacturing of steel semi-finished products, continuous casting quickly replaced ingot casting. Currently, thinner sheets can be obtained at the hot rolling stage and its production has increased while the cold rolling production has declined. Table 2 shows these changes in the share of the production by process between 1970 and 1996.

Mexico produces large quantities of DRI due to the high cost of scrap for the steel making process. In 1996, Mexico produced 11.5% of the world's DRI [5]. Most of the scrap consumed in the Mexican iron and steel industry is imported, which increases the production costs. Moreover, the Mexican company Hojalata y Lamina, S.A. (HYLSA) has developed its own technologies for DRI production: HYLI and HYLIII.[1]

Table 2
Iron and steel production by process in the Mexican iron and steel industry, 1970–1996 (share of the processes for each stage in percents)

	Production 1970 (Mt)	Production 1980 (Mt)	Production 1990 (Mt)	Production 1996 (Mt)
Iron making				
BF	1.6 (70%)	3.6 (67%)	3.7 (57%)	4.2 (51%)
DRI	0.6 (27%)	1.6 (30%)	2.5 (39%)	3.8 (46%)
Ferroalloys	0.1 (3%)	0.2 (3%)	0.3 (4.1%)	0.2 (3%)
Total	2.3(100%)	5.5 (100%)	6.5 (100%)	8.3 (100%)
Steel making				
OHF	2.3 (59%)	1.4 (19%)	0.7 (8%)	0.0 (0%)
BOF	0.0 (0%)	2.7 (38%)	3.5 (40%)	4.7 (36%)
EAF	1.6 (41%)	3.1 (43%)	4.5 (52%)	8.4 (64%)
Total	3.9(100%)	7.2 (100%)	8.7 (100%)	13.2 (100%)
Casting				
Ingot	3.5 (90%)	5.1 (71%)	3.2 (36%)	2.0 (15%)
Continuous	1.4 (10%)	2.1 (29%)	5.5 (64%)	11.2 (85%)
Rolling				
Hot rolling	1.9 (72%)	3.3 (70%)	4.5 (80%)	7.2 (81%)
Cold rolling	0.7 (28%)	1.4 (30%)	1.2 (20%)	1.6 (19%)

[1] HYL technologies produce DRI from iron ores using hydrogen (H_2) and carbon monoxide (CO) as reducing gases, high reducing temperatures and high operating pressures. HYLI refers to a fix-bed batch process, while HYLIII refers to a continuous process.

3.2. Primary energy use and related CO_2 emissions

The fuel mix of the Mexican iron and steel industry is closely related to activity trends. As mentioned, coke and natural gas are used as fuels and as reduction agents. In small quantities, natural gas and fuel oil are used to preheat and augment BOFs and EAFs. Electricity is mainly used in the EAF, but also in the rolling stages and in the oxygen production for the BOF. Fuels produced on-site in primary integrated steel plants, such as coke oven gas (COG) and blast furnace gas (BFG), are used to generate electricity for their on-site consumption [11,12].

At an aggregated level, the Mexican National Balance of Energy [4] reports the final energy consumption of these fuels (with the exception of the on-site produced energy) at integrated primary steel plants, secondary steel plants, foundries and mini-mills. Fig. 1 shows the energy consumption by fuel type from 1970 to 1996. Total primary energy consumption increased at an annual growth rate of 3.8% in this period.[2] Specifically fossil fuel consumption grew by 3.4% annually, while electricity consumption rose by 5.1% (see Table 1).

Again, the trends show different growth rates: total primary energy consumption increased at an annual rate of 5.8% from 1970 to 1980, (due to production expansion to satisfy domestic demand), dropping to 3.3% from 1980 to 1989 (due to an economic recession which led to a decline of steel demand), further dropping to −6.4% between 1989 and 1991 (during the privatization of the state-owned integrated plants), and finally rising again by 5.2% per year from 1991

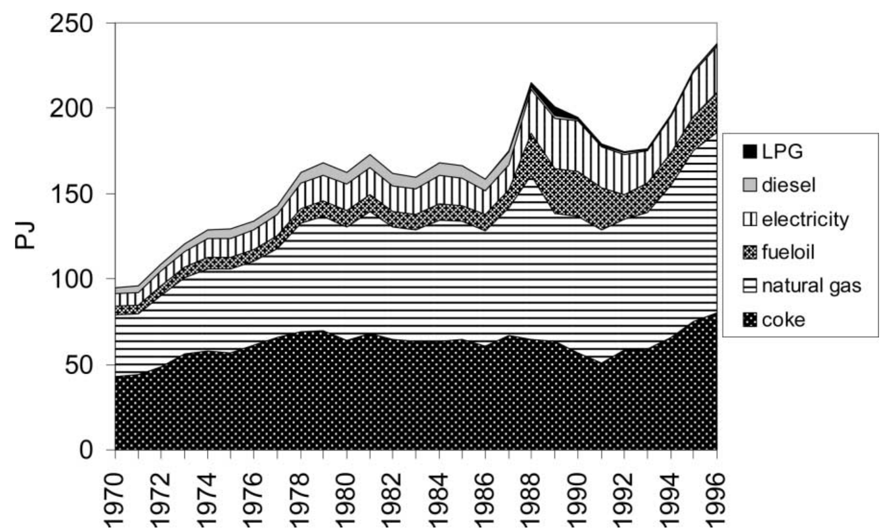

Fig. 1. Final energy consumption by fuel in the Mexican iron and steel industry, 1970–1996.

[2] Primary energy consumption considers the electricity generation efficiency, according to data from the National Balance of energy, and it is calculated as:

$$E_{p,t}=\sum_k E_{k,t}+\frac{E_{e,t}}{\eta_{e,t}}$$

where η_e is the electricity generation efficiency on year t, $E_{e,t}$ is the electricity consumption on year t and $E_{k,t}$ is the final energy consumption of fossil fuel k.

to 1996 (due to an increasing demand and a growth of exports). In particular, natural gas consumption grew at a faster annual rate (4.2%) than coke consumption (2.4%) over the entire period. This can be explained by the greater growth rate of DRI production (7.2%) compared to the pig iron production rate (3.7%). Electricity consumption increased by 5.1% between 1970 and 1996, tracking increases in EAF production (see Table 1).

Total CO_2 emissions from steel making in Mexico were estimated using the IPCC methodology [13]. Carbon emission factors for fossil fuels used in the iron and steel industry are: coke, 25.8 kg C/GJ; diesel, 20.2 kg C/GJ; kerosene, 19.6 kg C/GJ; LPG, 17.2 kg C/GJ; fuel oil, 21.1 kg C/GJ and natural gas, 15.3 kg C/GJ. The electricity carbon emission factor varied over time, depending on the power generation efficiency and the mix of primary energy sources.[3] Between 1970 and 1996, the participation of fossil fuels in total power generation increased from 43.1% to 70.0%, while hydroelectricity participation dropped from 56.9% to 20.7% [4]. As a result, the electricity carbon emission factor rose drastically from 36.9 kg C/GJ to 51.8 kg C/GJ, despite an increase of power generation energy efficiency from 22.0% in 1970 to 29.8% in 1996.

Total CO_2 emissions from the Mexican iron and steel industry increased from 2.1 million mt C (MtC) in 1970 to 5.6 MtC in 1996, at an annual rate of 3.8%. During the same period, the carbon emissions intensity (CEI, CO_2 emissions per tonne of steel) dropped from 0.55 to 0.43 mt C/tcs (21.9%).

4. Methodology

To understand the factors that influenced energy consumption and related CO_2 emissions in the Mexican iron and steel industry, we used a decomposition analysis methodology proposed by Farla et al. [8,14]. Following the recommendation of the *Handbook on international comparisons of energy efficiency in the manufacturing industry* [15], we used physical units for the activity and energy efficiency indicators. Total energy consumption of this industry is a function of the production volume (activity), the process and product mix (structure) and the energy efficiency of the production process. We also used a physical production index (PPI) in order to track the changes in time of the composition of the steel product mix. The PPI for each year t is calculated as:

$$\mathrm{PPI}=\sum_{i=1}^{n}(P_i \mathrm{SEC}_{BP_i}) \tag{1}$$

where P_i is the production of the steel product i and $\mathrm{SEC}_{BP,i}$ is a weighting factor based on the

[3] The electricity carbon emission factor was estimated as:

$$\mathrm{CEF}_e=\frac{\sum_j \mathrm{CEF}_j E_j}{\text{Net produced electricity}}$$

where CEF_e is the electricity carbon emission factor, CEF_j is the carbon emission factor of the fuel j and E_j is the energy consumption of fuel j for producing electricity.

energy consumed to produce the steel product *i* using the existing best practice. Table 3 depicts the weighting factors used in our analysis.

According to the international comparisons methodology [15], the SEC is influenced by the process and product mix, i.e. the feedstock used in the process (iron ore and scrap for the primary steel or only scrap for the secondary steel), the type of final products (slabs, sheets, bars and billets), and by the energy efficiency of the manufacturing process.

Thus, the total energy consumption for each year, taking into account the PPI, is given by:

$$E_t = \sum P \frac{\mathrm{PPI}}{\sum P} \frac{\sum E}{\mathrm{PPI}} \tag{2}$$

where the simple summation of the different products ΣP is the parameter of activity; PPI/ΣP gives the structure parameter and ΣE/PPI gives the energy efficiency parameter of the production processes.

Similar to energy use, CO_2 emission decomposition index, using PPI, can be expressed by:

$$CO_2 = \sum P \frac{\mathrm{PPI}}{\sum P} \frac{\sum E}{\mathrm{PPI}} \left(\sum_j \left[\mathrm{CEF}_j \frac{E_j}{E_T} \right] \right) \tag{3}$$

where ΣP is the parameter of activity, PPI/ΣP is the parameter of structure, ΣE/PPI is the parameter of energy efficiency, CEF_j is the CO_2 emission factor of fuel *j*, and E_j/E_T is the share of fuel *j* in the total final energy consumption. We added a fuel mix parameter that considers the mix of energy sources at the iron and steel industry as well as in the power sector.

To examine the changes, we calculated the simple average decomposition indices (AVE-PDM2)

Table 3
Best practice specific energy consumption for different processes in the iron and steel industry

Process	Best practice SEC_f (GJ/tcs)	Best practice SEC_e (GJ_e/tcs)	Best practice SEC_p[g] (GJ/tcs)
BF[a]	15.19	0.26	15.98
DRI[b]	11.19	0.17	11.71
BOF+casting[c]	0.57	0.12	0.93
EAF+casting[d]	0.79	1.52	5.40
Hot strip mill[e]	1.82	0.37	2.94
Cold rolling mill[f]	1.10	0.53	2.71

[a] The SEC of the blast furnace process considers the iron ore preparation of an integrated plant of the Netherlands in 1988, assuming a blast furnace feed of 50% pellets and 50% sinter [16].
[b] The SEC of the direct reduction process considers pellet preparation and it is based on a HYL plant of Mexico [17].
[c] The SEC of the BOF process and continuous casting is for an integrated plant of the Netherlands in 1988 [16].
[d] The SEC of the EAF and continuous casting is considered for a plant in Germany [16].
[e] The SEC of a hot strip mill of an integrated plant at the Netherlands in 1988 [16].
[f] The SEC of a cold rolling mill at an integrated plant in the Netherlands [16].
[g] Assuming an electricity generation efficiency of 33%.

using a rolling base year, due to the data availability and the small residual term [6]. The AVE-PDM2 indices examines the historical energy consumption and CO_2 emissions in a symmetrical manner with respect to time [7,8].

$$\Delta E_{t_0,T}=\sum_{t=0}^{T-1} E_{t,t+1(\mathrm{act})}+\sum_{t=0}^{T-1} E_{t,t+1(\mathrm{str})}+\sum_{t=0}^{T-1} E_{t,t+1(\mathrm{eff})}+R \tag{4}$$

$$\Delta \mathrm{CO}_{2t_0,T}=\sum_{t=0}^{T-1} \mathrm{CO}_{2t,t+1(\mathrm{act})}+\sum_{t=0}^{T-1} \mathrm{CO}_{2t,t+1(\mathrm{str})}+\sum_{t=0}^{T-1} \mathrm{CO}_{2t,t+1(\mathrm{eff})}+\sum_{t=0}^{T-1} \mathrm{CO}_{2t,t+1(\mathrm{fuel\ mix})}+R \tag{5}$$

The decomposition indices show the influences of changes in activity, in structure and in energy efficiency on total energy consumption between year t_0 and year T. Similarly, the indices indicate the effects of fuel mix and CO_2 emission factors on the total CO_2 emissions. It is important to note that each effect of activity, structure, energy efficiency, fuel mix and CO_2 emission factor assumes that the other variables remain constant, while the analyzed variable changes over time. Results are given in energy units.

Additionally, we used a structure/efficiency analysis to compare the SEC over time and between countries and to estimate the technical energy efficiency potential. The international comparisons methodology [15] recommends illustrating the SEC as a function of the changes in product mix (structure), and the energy efficiency as a function of the structure/efficiency trends [15]. Due to the high share of DRI input in EAF steelmaking at the Mexican iron and steel production, we considered the share of scrap input in the iron and steel making as the most representative structural factor [18].

5. Results of decomposition analysis

5.1. Energy use and SEC changes

According to the decomposition analysis, the substantial growth in steel production (activity) was the main factor that drove the huge increase in energy consumption. This activity effect would have increased the primary energy consumption to 256.3 PJ (211% more than the actual increase) if structure and energy efficiency had remained constant at 1970 levels. However, if production output and energy efficiency had remained constant, the changes in process and product mix (structure) would have decreased energy use by 15 PJ (12% less than actual). Likewise, the changes in energy efficiency would have lowered energy use by 61.6 PJ (51% less than actual) if the production volume and the structure had remained constant. Table 4 presents these changes that influenced the primary energy consumption between 1970 and 1996.

It is clear that the contribution of changes in energy efficiency and structure to total primary energy use was minimized by the substantial increase of the production output. In order to assess the relative importance of the structural and efficiency effects on the primary SEC changes, we

Table 4
Changes in iron and steel industry primary energy consumption (1970–1996)

Effect	Changes (PJ)
Actual primary energy	179.7
Production volume (activity)	256.3
Production and process mix (structure)	−15.0
Energy efficiency	−61.6

analyzed them utilizing the same methodology as described in Section 4, but taking out the activity effect. Results are presented in Table 5. If energy efficiency had remained constant at 1970 levels, the SEC would have decreased by only −0.3 GJ/tcs. However, if structural changes had remained constant, energy efficiency would have decreased by 8.1 GJ/tcs.

These results show that the main factor that drove down the SEC was energy efficiency. The reasons for this decline are mainly the closing of OHF capacity by 1992, the increased use of the continuous casting (9.8% in 1970 to 85.0% in 1996) and the increased utilization of COG and BFG for electricity cogeneration in the integrated plants. In addition, DRI in Mexico is manufactured with the HYL technology which has implemented new developments, i.e. a continuous process HYLIII instead of the batch process HYLI and a pneumatic system that transports the hot DRI directly to the EAF using DRI reactor exhaust reducing gases and eliminating the cooling and reheating stages [19,20]. In terms of structural changes, they are mainly due to the reduced cold rolled steel production and to the increase of thin and ultra-thin hot rolled sheets.

Similar results were obtained using a structure/efficiency analysis, Fig. 2 shows the trends of actual primary SEC and an aggregate 'best practice' SEC versus the structural factor (share of scrap input) of the Mexican iron and steel industry for the 1985–1996 period.

The reasons for the increase in the SEC between 1987 and 1990 are uncertain, but probably this increase was due to a decline of the scrap input from 29.5% in 1987 to 27.8% in 1990 [18] which possibly led to an increase in the requirement of pig iron and DRI. It is important to remark that the state owned integrated iron and steel plants were privatized during this period. The decline of the SEC between 1990 and 1996 was due to the modernization and expansion of the DRI plants and EAF minimills installed capacity [21–24], to the closing of OHF steel making and to the growth of scrap input at the steel making.

Comparing the actual SEC and the best practice SEC, we estimated the energy efficiency techni-

Table 5
Changes in iron and steel industry primary specific energy consumption (1970–1996), without production volume

Effect	Changes (GJ/tcs)
Actual primary specific energy consumption	−8.4
Production and process mix (structure)	−0.3
Energy efficiency	−8.1

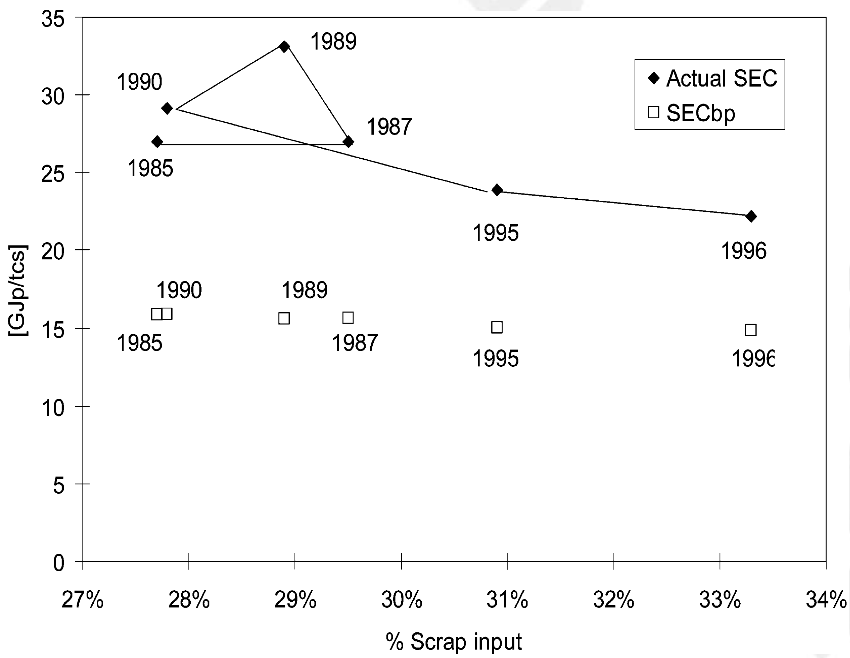

Fig. 2. Specific energy consumption in the Mexican iron and steel industry, 1985–1996. (Best practice SEC was calculated as:

$$SEC_{bp}=\frac{\sum P_i SEC_{bp_i}}{P_T}$$

$$=\frac{P_{pig\ iron}SEC_{bp\ pig\ iron}+P_{DRI}SEC_{bp\ DRI}+(P_{OHF}+P_{BOF})SEC_{bp\ BOF}+P_{EAF}SEC_{bp\ EAF}+(P_{HR}+P_{CR})SEC_{bp\ HR}+P_{CR}SEC_{bp\ CR}}{P_T}$$

where P_i is the output volume of the steel product i, P_T is the total steel production and $SEC_{bp\ i}$ is the best practice SEC for each steel product i (see Table 1).)

cal potential of the Mexican iron and steel industry. For 1996, this technical potential was 34% ±4%. In this case, uncertainties may be introduced due to the scrap input in the BOF and EAF. The heat balance in the BOF is affected by the use of scrap, while increased use of DRI (to replace scrap) raises electricity use in the EAF [25]. In earlier analyses a share of 10% scrap in BOF steelmaking has been used based on experiences in Europe [14]. However, this may not be the case for BOF-plants in Mexico.

Because we lack information on scrap inputs in the BOF in Mexican steel plants, we assumed the same BOF scrap input for our analysis. We have also not corrected the best-practice value for the electricity consumption of the EAF. The latter may lead to overestimating the potential for energy efficiency improvement, while the former may lead to underestimating the potential.

5.2. CO_2 emissions and CEI changes

CO_2 emissions are determined not only by activity, structural and energy efficiency changes, but also by the final fuel mix in the iron and steel industry and in the power generation. As

Table 6
Changes in iron and steel industry carbon dioxide emissions (1970–1996)

Effect	Changes (Mt C)
Actual carbon dioxide emissions	3.5
Production volume (activity)	4.8
Production and process mix (structure)	−0.2
Energy efficiency	−1.3
Fuel mix and fossil fuel carbon emission factor	0.2

mentioned above, from 1970 to 1996 the mix in energy sources used by the Mexican iron and steel industry had changed. The use of lower carbon fuels like natural gas increased due to growth DRI production. Whereas, electricity consumption rose considerably due to the increase in EAF production.

As mentioned in Section 3, the CO_2 emission factor for electricity also increased during this period due to an expansion of fuel oil and natural gas power plants substituting hydroelectricity.

Total CO_2 emissions have grown similarly to primary energy consumption due to the increase in steel production. But in this case, changes in fuel mix also contributed to the increased carbon emissions. If production, energy efficiency and process and product mix had remained constant, the CO_2 emissions would have increased by 0.2 MtC (9% of actual emission growth). The effect of this change is presented in Table 6.

To assess the relative importance of the efficiency, structural shift, and fuel mix effects, we also analyzed changes in CEI removing the activity effect. Table 7 shows that just as the decrease of the SEC, the technological changes which improved the energy efficiency of this industry were the main factors contributing to the decline of the CEI.

6. International comparisons of the Mexican iron and steel industry energy use

We compared the Mexican iron and steel industry energy use with five of the largest world steel producers: Japan (13.2%), United States (12.7%), Germany, F.R. (5.3%), Brazil (3.4%) and France (2.4%); using production, energy use and production mix data from INEDIS (International

Table 7
Changes in iron and steel industry physical intensity of carbon emissions (1970–1996), without production volume

Effect	Changes (kg C/tcs)
Actual physical intensity of carbon emissions	119.3
Production and process mix (structure)	23.0
Energy efficiency	−185.3
Fuel mix and fossil fuel carbon emission factor	42.9

Network on Energy Demand analysis in the Industrial Sector) [26]. As pointed out in Section 4, we used a structure/efficiency analysis according to the international comparison methodology [15,16] to compare the energy efficiency of the iron and steel industries in these countries, taking into account the composition of product mix for each country. We estimated the 'best practice' primary SEC using the weighing factors defined in Table 3 and considering the process and product mix for each country. Fig. 3 illustrates the actual SEC and the 'best practice' SEC versus the share of scrap input in the steel making for the Mexican iron and steel industry in 1990 and in 1996, and for the five selected countries in 1990.

As shown in Fig. 3, iron and steel production was less energy intensive in Germany and Japan than in Brazil, Mexico and the United States. The low SEC of Germany is due to energy efficiency measures like recovery of BOF gases, increased use of pellets as blast furnace feed and an increase of on-site electricity production using recovered BFG [16].

On the other hand, in the US this industry had a high primary SEC, despite its relatively high scrap input. It would be expected that a higher share of scrap in its EAF plants would contribute to a low primary SEC due decreased energy use for iron production. However, the US iron and steel industry has a high SEC in different stages of its production processes (blast furnace, BOF, reheating furnaces and hot mill) for a variety of reasons [27].

As mentioned, the most distinguishing characteristic of the Mexican iron and steel industry is its high share of DRI production, which is used in EAFs to replace scrap. From 1990 to 1996, the differences between the 'best practice' SEC and the actual SEC decreased from 13.9 GJ/tcs to 7.6 GJ/tcs; i.e. the energy efficiency technical potential declined from 47% to 34%. Changes in structure and energy efficiency have led to a more efficient use of energy and materials. However, there is still a technical potential for reducing the SEC by 34 ± 4%. In this calculation, as was pointed out in Section 4, the potential for energy efficiency improvement is calculated based

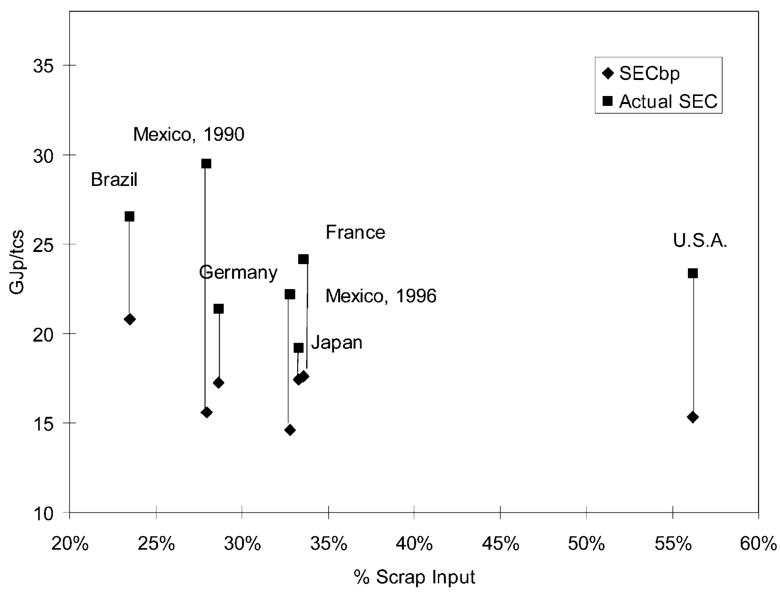

Fig. 3. International comparison of the iron and steel industry 1990 (and 1996 for Mexico).

on a break down of the main processes, so it recognizes the relatively high production level of DRI in Mexico, compared to other countries.

7. Conclusions

From 1970 to 1996, Mexican iron and steel production increased at an annual growth rate of 4.8%, leading to a 3.8% increase in primary energy consumption and related CO_2 emissions.

In the same period, the specific energy consumption dropped 8.4 GJ/tcs (27%) due to structural changes and energy efficiency improvements. Specifically, the technological changes that improved energy efficiency were: the complete substitution of OHF by BOF, a large increase of the share of continuous casting, the implementation of new technologies for DRI production and an increase use of coke oven and blast furnace gases for on-site electricity generation.

The structural changes that influenced the declining SEC were the increase of scrap input in the steel making process, and a growth of the share of hot rolled products, mainly ultra thin slabs, that were previously manufactured at the cold rolling stage mills.

The CEI decreased 0.12 tC/tcs (22%) in the period, as a result of energy efficiency improvements, and substitution of coke by natural gas (due to an increase of DRI production). However, the increasing electricity consumption, along with its increasing CO_2 emission factor in the steel production offset part of the efficiency gains.

During this period, the composition of both product mix and processes changed. In the last decade, the share of electric arc furnaces has grown at integrated plants as well as at mini mills. However, the main input for EAF steel making is DRI rather than scrap due to its high cost.

Despite the decline of SEC and CEI, the Mexican iron and steel industry still has a large reduction technical potential (34±4% in 1996) in comparison to other countries. This reduction can be achieved through the implementation of energy efficiency measures.

An analysis of the US steel industry identified a number of cost-effective measures at US 1994 prices [27]. We believe that these measures can be applicable to Mexico as well. For the overall production process, it is recommended to install process control and automation for a better measurement and management, to improve preventive maintenance and to implement variable speed drives for fans and pumps [27]. For particular stages, it is recommended to recover BFG for cogeneration at the pig iron production; to recover the sensible heat from BOF gas at the primary steel production; scrap preheating, foamy slag practice and oxy-fuel burners for reducing heat losses and for improving heat transference at the EAFs [27]. There are also technological developments for HYL DR reactors that can be implemented in a wide number of existing plants, such as a self reforming scheme, a HYLTEMP system for the pneumatic conveying of hot DRI to the EAF [21]. However, in the future it will be necessary to analyze the cost-effectiveness of these measures and of new technologies at Mexican energy prices.

It is also important to design new plants with the most energy-efficient technologies and the best practices for energy conservation. In order to reduce the SEC, a good option for the Mexican iron and steel industry would be to increase the share of scrap input at the electric arc furnaces. However, a rapid increase in scrap consumption is not expected because the domestic scrap market has not emerged yet and most of the scrap is imported and costly, which increases the production costs. Governmental efforts in the areas of collection and transportation incentives can be valuable to promote the recycling of steel scrap already used by domestic consumers. It will also help to reduce energy use and GHG emissions at the iron and steel production and to decrease solid wastes from the steel cycle.

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